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Lines of Descent: Kuhn and Beyond

Abstract

Thomas S. Kuhn is famous both for his work on the Copernican Revolution and his 'paradigm' view of scientific revolutions. But Kuhn later abandoned the notion of paradigm (and related notions) in favour of a more 'evolutionary' view of the history of science. Kuhn's position therefore moved closer to 'continuity' models of scientific progress, for instance 'chain-of-reasoning' models, originally championed by D. Shapere. The purpose of this paper is to contribute to the debate around Kuhn's new 'developmental' view and to evaluate these competing models with reference to some major innovations in the history of cosmology, from Copernicanism to modern cosmology. This evaluation is made possible through some unexpected overlap between Kuhn's earlier discontinuity model and various versions of the later continuity models. It is the thesis of this paper that the 'chain-of-reasoning' model accounts better for the cosmological evidence than both Kuhn's early paradigm model and his later developmental view of the history of science.

It is hard to think of an area of intellectual inquiry that has changed more in the past century than cosmology and the shift has transformed how we view the world. L. M. Krauss/R. J. Scherrer, *The End of Cosmology*, *Scientific American* 298/3 (2008), p. 46

I. Introduction

Thomas S. Kuhn is best known for his book *The Structure of Scientific Revolutions* (¹1962), which characterizes numerous brief episodes in the history of science, including Copernican heliocentrism, as 'revolutionary' periods. But Kuhn's most elaborate exploration of a scientific revolution is provided by the masterly analysis in his earlier book *The Copernican Revolution* (1957). In this book, Kuhn describes Copernicus as a *precursor* of a scientific revolution. His book *De Revolutionibus* (1543) is a 'revolution-making rather than a revolutionary text.' (Kuhn 1957, p. 183) For readers unfamiliar with the astronomical theory of Nicholas Copernicus (1473-1543), it may be useful to remind them of some of his achievements. In a departure from a long tradition, which had its roots in Greek thought, Copernicus proposed a *heliocentric* view of the universe, in opposition to the established *geocentric* view, whose chief contributors were Aristotle (354-322 BC) and Ptolemy (100-175 AD). Copernicus made the Earth a planet, which orbited the central (mean) sun. To place the sun at the centre of the then known universe was not in itself an original idea. The Greek astronomer Aristarchus of Samos (circa 310-230 BC) had already constructed a heliocentric world system, which made the Earth rotate daily on its own axis and annually around the sun. The diurnal rotation of the Earth was proposed by several thinkers throughout the ages (Herakleides, Buridan, Oresme, Nicolaus of Cues). But no technical details of Aristarchus's system have survived so that Copernicus became the first known astronomer to construct a coherent, mathematical system of planetary motion from a heliocentric perspective. In the Greek tradition all the planets and their motions were treated separately but Copernicus's aim was to derive all the observational data of the planets' orbits from the assumption of a moving Earth. Thus Copernicus was the first astronomer to propose a detailed account of the astronomical consequences of the Earth's motion, as part of a planetary system. (Kuhn 1957, pp. 142-4; Weinert 2009, §3.1) It is important to observe that although Copernicus reports his own observations of the sky, his observations do not reach beyond the discoveries of his Greek predecessors. He does not discover *new* facts about the planets. It is equally important to realize that Copernicus still adheres to much of the Greek tradition in his mathematical techniques. Like his illustrious Greek predecessors, Aristotle and Ptolemy, he uses geometry to describe the motions of the then known 6 planets. Most importantly, Copernicus does not abandon the fundamental Greek idea that all celestial objects must move in circles around a central body, since the circle was the most perfect geometric figure. Perfection and harmony, to the Greek mind, characterized the heavens.

Given these few rudimentary facts about the Copernican system, especially his profound indebtedness to the Greek tradition, the obvious question, which many historians of science have asked, is whether the Copernican model constitutes a scientific revolution. The epithet 'Copernican revolution' is sometimes bestowed on the whole period from the publication of the Copernican treatise (1543) to the publication of Newton's *Principia* (1687) and sometimes on the Copernican theory itself. In the present context the question is only whether the Copernican theory itself is revolutionary, since there is little disagreement that the period from Copernicus to Newton constitutes indeed a scientific revolution. But such questions cannot be settled without some pre-given criteria of what constitutes a scientific revolution. Historical judgements on this question have therefore varied widely. The historian of science De Solla Price saw in Copernicus's book 'little more than a reshuffled version of [Ptolemy's] *Almagest*'. (De Solla Price 1962, p. 215) Arthur Koestler also detected little originality in Copernicus, characterizing him as a 'stuffy pedant', but also recognized in him a 'crystallizer of thought'. (Koestler 1964, pp. 205, 113) E. Rosen found that 'Copernicus did not foment a "Copernican Revolution"' (Rosen 1984, pp. 132-3), whilst for A. C. Crombie (1961, p. 168) the Copernican Revolution consisted in the link Copernicus established between the diurnal and annual revolution of the Earth and the motion of the planets. J. H. Randall (1962, pp. 308-15) was more willing to grant Copernicus the title of a scientific revolutionary, whilst H. Blumenberg (1955; 1965) acknowledged Copernicus above all as an intellectual reformer. Similarly, for O. Gingerich, Copernicus was a 'sensitive visionary who precipitated a scientific revolution.' (Gingerich 1993, p. 201) Reflecting these divergent assessments of Copernicus's achievement, we observe in Kuhn's work a transition from a conservative to a liberal view in the span of a few years (1957-62), which may be attributed to a change in his views on what constitutes a scientific revolution.

II. Kuhn's assessment of Copernicus

Kuhn's most careful exploration of a scientific revolution is to be found in his analysis of the early history of astronomy from the Greeks to Newton. In this book *The Copernican Revolution* (1957) Kuhn goes beyond the assessments of de Solla Price and Koestler and agrees with O. Gingerich that Copernicus is best described as a precursor of a scientific revolution. Unlike Rosen he sees in Copernicus's book *De Revolutionibus* (1543) a 'revolution-making rather than a revolutionary text.' (Kuhn 1957, p. 183) The Copernican system has aesthetic advantages, since it derives from the principle of a moving Earth a natural explanation of one of the gross planetary irregularities in Greek astronomy: the apparent retrograde (westward) motion of planets becomes a matter of the perspective of an Earth-bound observer who assesses the motion of planets around the sun against the background of the fixed stars. Although Copernicus abides by the Greek notion of uniform circular motion, he departs from Ptolemy by adopting a simple 'distance-period' relationship to assess the relative distances of the planets from the sun. The rule states that the further a planet is away from the sun, the longer is its orbital period. But Copernicus produced no decisive evidence, which could demonstrate that a Copernican hypothesis is more probable

than a geocentric hypothesis. However, Kuhn's tone changes in *Structure*, where he states, in many passages, that the replacement of Aristotelian-Ptolemaic geocentrism by Copernican heliocentrism is a paragon of a scientific revolution. Copernicus is discussed in the same breath as Newton, Lavoisier and Einstein and is hailed as the originator of a new paradigm. (Kuhn 1970a, pp. 6, 66, 92, 116, 180, 200)

Of central importance in the present context is the question whether the Copernican model of 1543 was a scientific revolution or a precursor to a scientific revolution – two aspects of Kuhn's assessment of the situation.¹ As mentioned before the answer to this question depends on the criteria adopted but, crucially, the criteria themselves must be adequate for a historical judgement of a particular episode, like the Copernican heliocentric model. Before these criteria are discussed, it will be helpful to add some further historical material regarding the Copernican model. It has already been mentioned that Copernicus's commitment to circular orbits and geometry marks a significant element of *continuity* between his work and that of his Greek predecessors. But there is also a significant element of *discontinuity*, hinted at by Crombie, which has not been sufficiently emphasized in the literature. Copernicus becomes the first astronomer to successfully treat the planets and the sun as a coherent *system*. The cosmologist, Aristotle, provided a qualitative model of the whole cosmos but Aristotle's astronomical, concentric model of the planetary system failed because it did not respect the 'distance-period' relationship. Ptolemy, the mathematical astronomer, accepted Aristotle's cosmological principles – especially the centrality of a stationary Earth – but, for computational reasons, treated each planet separately and in isolation from each other. Copernicus binds the planets into a coherent system, with the sun at the 'centre', such that the removal or displacement of one element would disrupt the entire system. Such a commitment imposes an important constraint on the model.

And so, having laid down the movements which I attribute to the Earth farther on in the work, I finally discovered by the help of long and numerous observations that if the movements of the other wandering stars are correlated with the circular movement of the Earth, and if the movements are computed in accordance with the revolution of each planet, not only do all their phenomena follow from that but also this correlation binds together so closely the order and magnitudes of all the planets and of their spheres or orbital circles and the heavens themselves that nothing can be shifted around in any part of them without disrupting the remaining parts and the universe as a whole. (Copernicus 1543, p. 6)

The conception of the coherence of planetary phenomena obliges the Copernicans to build a model of the planetary system, which must accommodate all the known empirical data. They were not altogether successful but the balance of successes and failures of the Copernican system provides useful indicators as to the criteria of scientific revolutions. Given these main lines of continuity and discontinuity it may be best to characterize Copernicus's work as a Copernican *turn*: a change in perspective but not a revolution, in line

¹ One may want to avoid such considerations by concentrating on the role of new premises in the transition between theories (cf. Vickers 2013) but Kuhn's concern throughout his career has been with the nature of scientific revolutions.

with Kuhn's original 1957 verdict. As will be discussed, later on M. Maestlin and J. Kepler produced plausibility arguments in favour of the Copernican model. This cautious assessment depends of course on some chosen criteria, which may serve to characterize a scientific revolution. But it is supported by the lines of continuity and discontinuity, which have emerged in the Copernican story. In order to arrive at some acceptable criteria it will be convenient to compare views of scientific revolutions, which put the emphasis on such lines of descent, which include Kuhn's 'paradigm' view and his later 'evolutionary' view, as well as the 'chain-of-reasoning' model.²

III. Lines of Descent

In the first edition of his famous book *The Structure of Scientific Revolutions* (¹1962) Kuhn presented a 'discontinuity' view of the history of scientific thinking, based on the notion of paradigm change. (Kuhn 1970a; cf. Kuhn 1978, p. 362) This discontinuity view is accompanied by an acceptance of cumulative growth, which is restricted to periods of normal science. By contrast Popper defended a 'continuity' model, based on conjectures, error elimination and tentative solutions. Popper's conjectures and refutations allow for discontinuity, since falsified theories must be eliminated and replaced by better theories. Popper nevertheless defends a Lamarckian view of the progress of science, since he sees science as aiming at truth and asymptotically approaching it (verisimilitude).³ This Lamarckian view implies a cumulative image of the growth of scientific knowledge. The idea of degrees of verisimilitude may hold only between two theories. Theory T_2 , for instance, is 'better' than theory T_1 , if it passes more stringent tests than T_1 . But Popper also proposes a global sense of verisimilitude as an ideal.

Verisimilitude is so defined that maximum verisimilitude would be achieved only by a theory which is not only true, but completely comprehensively true: if it corresponds to all facts, as it were, and, of course, only to real facts. This is of course a much more remote and unattainable ideal than a mere correspondence with some facts (...). (Popper 1963, p. 234; emphasis in original)

Popper defends a correspondence theory of truth, which Kuhn disavows. (Kuhn 1990/2000, pp. 99-100; 1991/2000, p. 115) Kuhn deserves credit for a) having put the notion of scientific revolutions firmly on the agenda of the philosophy of science and b) for having drawn attention to discontinuities between scientific theories, separated by the gulf of a scientific revolution. In doing so Kuhn posed a challenge to the traditional ideas of cumulative scientific progress. For instance, Kuhn treats the theory of relativity as a revolutionary paradigm change and defends the 'minority view' that 'Einstein's theory can

² The paper will focus on the approaches developed by Kuhn and, in response, by Shapere, respectively, because of their agreement on lines of descent. Cohen's 4-stage model of scientific revolutions (Cohen 1985) and Friedman's views on 'inter-paradigm convergence' (Friedman 2001, Pt. I, §3; Pt. II, §3) are versions of the 'chain-of-reasoning' approach. Friedman, for instance, discusses 'transformations of old constitutive frameworks' (2001, p. 101), which give rise to lines of descent between paradigms.

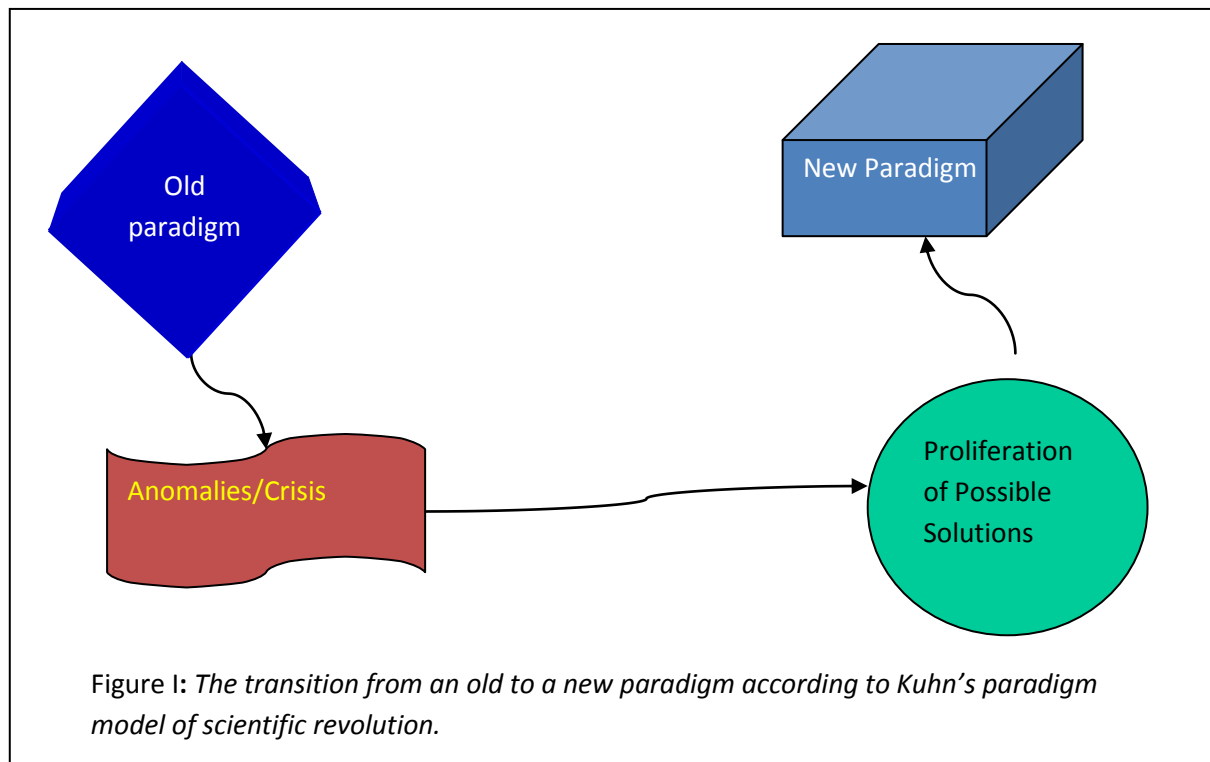
³ An evolutionary analogy of the growth of science may not be compatible with truth or verisimilitude as the aims of science; see the discussion in Rowbottom (2010)

be accepted only with the recognition that Newton was wrong.’ (Kuhn 1970a, pp. 98, 102; 1986/2000, p. 74) Kuhn adopts a strictly non-teleological image of scientific development as unidirectional, irreversible growth. He employs the image of the survival of the fittest. (Kuhn 1970a, pp. 172, 206; cf. Bird 2011, §2) According to this view science does not grow towards some ultimate aim but adapts in response to the growing complexity of the problem situations, which comprise the (perceived) problem(s), at a particular epoch, the available techniques, empirical data and presuppositions. If there is an aim it is to find the ‘fittest way to practice future science’ (Kuhn 1970a, p. 172) or to maximize efficiency in puzzle-solving (Kuhn 1983, p. 563/2000, p. 209; 1990/2000, p. 96). Still the ‘Postscript’ makes clear that theories are to be seen as ‘related by descent’. (Kuhn 1970a, p. 205) A Darwinian image of an evolutionary tree implies both a discontinuous view of the growth of scientific knowledge – like species, old theories may become extinct – but retains continuous elements – like species, theories adapt to a ‘more refined understanding of nature.’ (Kuhn 1970a, p. 170) Replacements of old paradigms are not cumulative; they appear like mere change because scientific revolutions lead to a reconfiguration of the map of knowledge. (Kuhn 1975; Shapere 1980, p.35; Díez 2007) Kuhn’s intention was to provide a language, a framework, with which scientific revolutions could be investigated and analyzed (paradigm, incommensurability, meaning variance, communication breakdown and relativism). According to this framework scientific revolutions are ultimately changes in world views. But, as just indicated, even successive paradigms are linked by lines of descent and hence one can expect both continuity and discontinuity. As Kuhn’s views evolved the emphasis shifted from discontinuity to continuity. As the later Kuhn began to stress the importance of incremental changes his views began to resemble the ‘chain-reasoning’ approach. Early signs of this shift can already be discerned in his ‘paradigm’ model of scientific revolutions.

A. Kuhn’s Paradigm Model of Scientific Revolutions.

According to the early Kuhn, the history of science consists of a series of ‘pre-paradigm’, ‘normal’ and ‘extraordinary’ periods. (Kuhn 1970a; cf. Hoyningen-Huene 1993) A pre-paradigm period is a stage of a science when no dominant paradigm has yet appeared and a number of theories compete with each other for dominance. A normal period of science is marked by the presence of a dominant paradigm. Hence there is a scarcity of competing schools during periods of normal science. (Kuhn 1970a, p. 209) This paradigm is accepted as a valid framework for ongoing research. During periods of normal science, scientists are involved in problem-solving. The accepted problems, techniques and solutions are set by the ruling paradigm. Typical examples of paradigms are heliocentric astronomy, Newtonian mechanics, and Darwinian evolutionary biology. During normal periods of science, the practitioners of a scientific discipline accept the basic presuppositions of the paradigm. Their work consists in refining the representational force and explanatory power of the paradigm. Eventually, however, any period of normal science faces a crisis. It may then enter a period of extraordinary science. A crisis in science can happen for a number of reasons, for instance

as a consequence of the introduction of new laws or instruments. (Kuhn 1970a, p. 181) But it is, according to Kuhn, mostly associated with the failure of a paradigm to deal with all the phenomena in its domain. A crisis emerges when a paradigm faces significant *anomalies*. An anomaly occurs when there is a persistent disagreement between a theory's predictions and the measured observations.⁴ If scientists fail to solve the problem, they may react in a number of ways: one is to shelve the problem; another is to let the discipline enter a *revolutionary period*. During such a period a number of competitors vie for dominance, until eventually a new paradigm prevails. (Figure I)



A paradigm is a conceptual scheme which mediates the interaction between the scientist and the world of phenomena. It facilitates the mapping of symbolic structures onto the empirical world. According to Kuhn, scientists can only inhabit one paradigm at a time. It determines their world view and it takes a gestalt switch to convert them to a different paradigm. (Kuhn 1970a; Kuhn 1970b; Kuhn 1978, p. 363; cf. Nola 2003) They find it even difficult to talk to each other, because they inhabit 'different worlds'.

If this is the case why do paradigm shifts take place at all? Kuhn's answer is that the seeds of revolutionary change are built into each paradigm. Each paradigm eventually enters a crisis period, due to anomalies or other factors. It is often younger scientists who initiate the process.

⁴ Salmon (1990, p. 193) characterizes an anomaly as a 'phenomenon that appears to have a small, possibly zero, likelihood given that theory.'

The transition to a new paradigm introduces a large number of discontinuities in the growth of scientific knowledge. The whole conceptual network changes with respect to a) the meaning and reference of central terms; b) its ontology or the accepted 'furniture' of the world: 'What were ducks in the scientist's world before the revolution are rabbits afterwards.' (Kuhn 1970a, p. 111); c) acceptable problems and techniques; d) incommensurability⁵: the conceptual networks are characterized by the rules of a particular paradigm, the elements of which are judged to be 'incommensurable' between successive paradigms. Although Kuhn accepts that successive paradigms can be compared, he holds that they cannot be translated into each other because of the non-compatibility of the components of one paradigm with another. For example Kuhn claims that the Earth became a planet only in the new heliocentric paradigm; d) the adoption of a new paradigm is a case of conversion and persuasion, for which rational reasons alone are not compelling.

In terms of lines of descent Kuhn therefore emphasizes discontinuous breaks, without however completely abandoning lines of continuity, since a new paradigm must preserve past achievements. (Cf. Hoyningen-Huene 1993, §7.6; Worrall 2003; Rowbottom 2012)

Contrary to Kuhn's assertion in *Structure*, the Copernican turn does not really fit the Kuhnian paradigm model. Historians agree that astronomy was not in a state of crisis when Copernicus began his work. (Gingerich 1993; Kragh 2007, §1.4; Heidelberger 1980) Kuhn holds that crises may only be a 'useful prelude' to scientific revolutions but adds that a crisis is indispensable for a profound change of theory. (Kuhn 1961, §4; 1970a, p. 181) Yet other features show that the Copernican turn does not fit the paradigm model of scientific revolutions. No new anomalous observations threatened the Ptolemaic model. Copernicus did not invent new techniques to describe planetary motion. The Copernican version of heliocentrism is hardly incommensurable with geocentrism because of the large overlap between the two systems (even though the term 'planet' began to be applied to the Earth; cf. Kuhn 1970a, 149-50). Copernicus uses many of the Greek observations and their mathematical techniques. Most decisively, Copernicus adheres to the Greek dogma of circular motion. It is hard to detect as much as a partial breakdown of communication, which Kuhn continues to see as a feature of a crisis. (Kuhn 1990/2000, p. 100) As we shall see, the Copernicans employed plausibility arguments to demonstrate that geocentrism had much less probability, in the face of evidence, than heliocentrism. Rather than constituting a paradigm shift, Copernicus's work represents a change of perspective, which instructs the astronomer to describe the phenomena from a heliocentric rather than a geocentric viewpoint. The small changes between geocentrism and Copernican heliocentrism did produce large-scale effects (Kuhn 1990/2000, p. 104), but only in the long run. The more mature Kuhn begins to focus on incremental changes and continuity.

⁵ Several senses of 'incommensurability' can be distinguished in Kuhn's work (see Bird 2011; Wray 2011, 65-77); the most recent one, as discussed below, is taxonomic incommensurability

B. Kuhn's developmental view

In his 'Postscript', in response to criticism, Kuhn proposes a new terminology, i.e. disciplinary matrix (consisting of symbolic generalizations, belief in particular models, values, as well as exemplars – or paradigms, now meaning 'shared' examples).⁶ But he continued to be preoccupied by the problem of 'incommensurability', which came to mean 'untranslatability localized to one or another area, in which two lexical taxonomies differ.' (Kuhn 1990/2000, p. 93) Kuhn began to stress that scientific communities share a certain lexicon, with shared meaning and referents of the terms employed, and that different lexicons imposed different structures on the world: hence the problem of untranslatability as a localized problem between divergent lexicons. Different lexicons are different sets of possible worlds, 'largely but never entirely overlapping.' (Kuhn 1986/2000, p. 61; 2000, Part 1) What is of interest in the present context is that Kuhn characterizes his 'mature' position as Post-Darwinian Kantianism. (Kuhn 1990/2000, p. 104) The lexicons of scientific practitioners function like Kant's categories – as preconditions of possible experience – but unlike the unchanging Kantian *a priori* categories they are *a posteriori* and subject to change. The term also indicates Kuhn's return to evolutionary views, which first emerged in *Structure*: a) remaining faithful to his earlier views he still believes that science has no overriding epistemic aim (like verisimilitude), since the history of science should be regarded as 'evolution from' not 'evolution towards'; b) the early distinction between 'normal' and 'revolutionary' science is now replaced by the distinction 'between developments which do and developments which do not require local taxonomic change.' (Kuhn 1990/2000, p. 97); c) scientific revolutions are now to be regarded as analogous to 'episodes of speciation in biological evolution.' (Kuhn 1990/2000, p. 98; cf. Bradie 1986; Kuukkanen 2012)

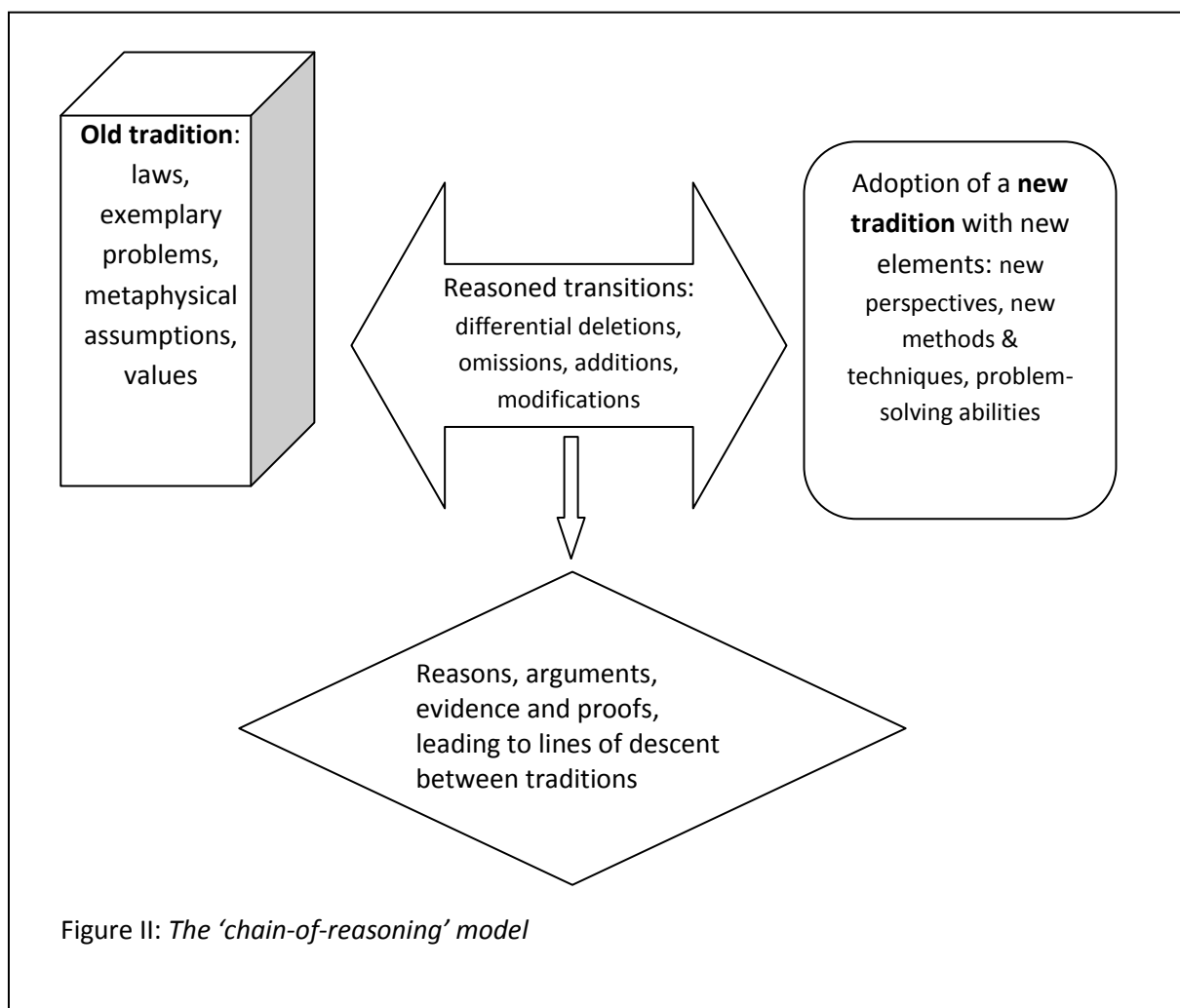
However one may judge the 'lexicon-dependent structuring of the world', Kuhn's shift to the role of lexicons makes his narrative of the history of science more descriptive. The developmental view tends to emphasize how the meaning and reference of central terms, like 'planet', 'mass' change but it does not tell us *why* they change. Yet Kuhn does not abandon the aspect of evaluation. It is for this reason that alternative models of scientific growth are still of great relevance, in particular the 'chain-of-reasoning' model, which puts the emphasis on *why*, not just on *how*, theories, paradigm, lexicons or traditions change.

C. Shapere's Model of Scientific Revolutions.

In the light of Kuhn's paradigm model it was therefore hardly surprising that the analysis of historical case studies produced alternative models of scientific change, which pay more attention to questions of 'descent with modifications' but bear some resemblance to Kuhn's later views. Of particular interest is Shapere's 'chain-of-reasoning model' because it encapsulates the salient features of continuity models and places strong emphasis on lines

⁶ For further discussions of the notions of 'paradigm' and 'disciplinary matrix' see Rowbottom (2011); Hoyningen-Huene (1993)

of descent. (Shapere 1966; 1989; Cohen 1985; Friedman 2001; cf. Weinert 1982) According to this model, the history of scientific ideas displays a transitional pattern, which captures both elements of continuity and discontinuity. Scientific revolutions constitute radical transitions (with fewer lines of continuity than discontinuity) but not discontinuous breaks. Instead of using the terminology of paradigms, the model speaks of ‘traditions’, which are characterized as conceptual networks, whose elements change differentially over time. Furthermore, these changes happen as a result of arguments and evidence, which means that we can speak of *reasoned* transitions between the conceptual components of the networks. These reasons are not just ‘values’, as in Kuhn’s view, which can then be applied differentially by different scientists. The reasons are of an empirical and theoretical nature



and they justify the transitions between traditions. Traditions are therefore linked by ‘lines of descent’ with modifications. The career of, say, the notion of circular orbs from Greek to post-Copernican astronomy, through medieval contributions, like the impetus theory of motion, can be pursued and it be can understood why it became obsolete. This is an example of a reasoned transition because it arises from a problem situation, in which attempted solutions are evaluated through a chain of reasons and arguments. The transitions lead to the reorganization of at least part of the conceptual scheme, and they are

part of problem-solving attempts. These attempts leave traceable lines of descent between scientific models. During these reasoned transitions the conceptual networks are subject to various epistemological operations, like additions, deletions, omissions, modifications and replacements. (Figures II, III)

What makes a comparison between Kuhn's discontinuity model and Shapere's continuity model possible is a two-fold rapprochement: 1) Kuhn's paradigm model can be described in the language of the 'chain-of-reasoning' model: Kuhn seems to maximize the role of deletions, claiming that there is a great amount of discontinuity between two successive paradigms (differences in ontology, redefinitions of the problem situation, including the acceptability of problems and the techniques for their solution, changes in conceptual repertoire and world views). At the same time a new paradigm is required to preserve a large part of the 'problem-solving ability' of its predecessor and to solve the anomalies, which plunged it into crisis. (Kuhn 1970a, p. 169) 2) In his later work Kuhn appeals to five criteria of theory choice: accuracy, consistency, scope, simplicity and fruitfulness. (Kuhn 1983; Kuhn 1970a, p. 42; Kuhn 1970b; cf. Earman 1993; McMullin 1990; Kragh 2013, §1) He insists that taken separately the criteria are imprecise, taken collectively they are incompatible. The criteria of evaluation are 'equivocal'. (Kuhn 1991/2000, p. 114) No single reason may influence theory choice for each member of a community. (Kuhn 1970a, 152) Hence they serve as values, not rules for theory choice. Nevertheless, in an afterthought, Kuhn grants that conformity, scope and fruitfulness could be regarded as 'invariant values' in the history of science, although through time they will be applied differentially by the scientific community. In order to dispel the impression of relativism, Kuhn insists that there are good reasons for adopting a new paradigm; but these reasons are interpreted as having the function of values and as such they are subject to differential assessment by scientific communities. They have persuasive functions for a group of practitioners. (Kuhn 1970a, pp. 199-200) His mature work returns to the question of evaluation. He now emphasizes the importance of incremental changes in the body of beliefs but evaluations are relative to scientific research communities, their lexicons and achieved standards at a given time.

(Evaluation) should be seen as a complex but unsystematic structure of distinct specialities or species, each responsible for a different domain of phenomena, and each dedicated to changing current beliefs about its domain in ways that increase its accuracy and the other standard criteria (...). (Kuhn 1990/2000, p. 119, cf. 1990/2000, p. 102)

There are several continuities between Kuhn's earlier and later work.⁷ One is that Kuhn insisted already in *Structure* that a new paradigm must display a better 'quantitative precision than its older competitor.' (Kuhn 1970a, pp. 153-4; cf. Kuhn 1961, §4; Kuhn 1975)

It makes a great deal of sense to ask which of two actual and competing theories fits the facts better. (Kuhn 1970a, pp. 147, cf. pp. 169, 172; italics in original)

⁷ For instance he remained critical of the correspondence theory of truth, of the assumption of a mind-independent world, which is linked to his continued interest in incommensurability and scientific revolutions.

This passage appears in Kuhn's discussion of Popper's falsification criterion. Kuhn affirms that the falsification of a theory is at the same time a confirmation of a competing theory. This discussion has a Bayesian flavour, as some commentators have noticed (Earman 1993; Salmon 1990), and which will be explored below (see Appendix). Kuhn's list of criteria makes no explicit reference to 'evidence' as a factor bearing on theory comparison and theory choice, but evidence can easily be subsumed under the criteria of accuracy and scope. (Cf. Worrall 2000, 135-6) Although Kuhn's position is that the evaluation of evidence – in terms of empirical data and theoretical proofs – is subject to changing emphasis on values, his position also implies that there is 'always an objectively correct judgement to be made about how various rival theories, at a given time, stand in relation to evidence.' But he continues to emphasize that such judgements remain specific to scientific sub-groups, which form their own lexicons.

In one form or another, the rules of the true/false game are thus universals for all human communities. But the result of applying those rules varies from one speech community to the next. In discussion between members of communities with differently structured lexicons, assertability and evidence play the same role for both only in areas (there are always a great many) where the two lexicons are congruent. (Kuhn 1990/2000, p. 100, cf. 1991/2000, pp. 111-6; 1970a, p. 155; Worrall 2003, p. 96; Worrall 2000, §3; Wray 2011, Part III)

With the emphasis on continuity and incremental growth, Kuhn's later 'historical perspective' moves much closer to the 'chain-of-reasoning' idea, which seeks a better balance between additions and deletions than Kuhn's early paradigm view. In certain passages Kuhn seems to grant the permanency of such values across revolutions.

Accuracy, precision, scope, simplicity, fruitfulness, consistency, and so on, simply are the criteria which puzzle solvers must weigh in deciding whether or not a given puzzle about the match between phenomena and belief has been solved. (...) As the developmental process continues, the examples from which practitioners learn to recognize accuracy, scope, simplicity, and so on, change both within and between fields. But the criteria that these examples illustrate are themselves necessarily permanent... (Kuhn 1973, pp. 338-9, quoted in Friedman 2001, pp. 50-1)

There is therefore some overlap, which may serve as a basis for comparison and evaluation. In terms of the terminology of reasoned transitions progress in science can be characterized as evolving problem situations, which are linked by the differential operations on their components; the solutions to the problems lead to more complex problems, which in turn lead to more complex solutions. This characterization does not prejudice the further issue of whether scientific evolution happens in a Lamarckian or Darwinian guise. In fact, Kuhn characterizes the strictly Darwinian picture as holding that the history of science can be described without employing the notion of truth. Instead there are taxonomic divergences, with the concomitant problem of 'incommensurability' and the possibility of partial communication breakdown. (Kuhn 1987; 1990; 1991) Indeed, in his later work Kuhn continues to emphasise his opposition to the correspondence theory of truth.

Finally, what replaces the one big mind-independent world about which scientists were once said to discover the truth is the variety of niches within which the practitioners of these various specialities practice their trade. Those niches, which both create and are created by the conceptual and instrumental tools with which their inhabitants practice upon them, are as solid, real resistant to arbitrary change as the external world was once said to be. But unlike the so-called external world, they are not independent of mind and culture, and they do not sum to a single coherent whole of which we and the practitioners of all the individual scientific specialities are inhabitants. (Kuhn 1991/2000, p. 120)

Kuhn's paradigm model of scientific revolutions does not describe the emergence of the heliocentric view in Copernicus's work very well. In his later work scientific revolutions are compared to biological speciation – or the emergence of specialized disciplines – but this is still characterized by non-cumulative growth. Revolutionary changes 'involve discoveries that cannot be accommodated with the concepts in use before they were made.' (Kuhn 1987/2000, p. 14; 1991/2000, pp. 119-20) The question arises whether the subsequent history of cosmology, with its many radical discoveries and changes – Newton's inverse-square law, the General theory of relativity, Hubble's law, the demise of the Steady State model in favour of Big Bang cosmologies, the discovery of the expanding and accelerating universe, inflationary scenarios and the multiverse – fit Kuhn's evolutionary model of scientific development any better. Or is the 'chain-of-reasoning' model better equipped to capture the essence of the changes, which took place between the time of Copernicus and modern cosmology? As both models agree on lines of descent, it may be asked in which sense cosmology experienced another scientific revolution?

IV. Main innovations in cosmology since Copernicus

The richness of the material in the history of cosmology is partly due to the mass of empirical discoveries, which do not necessarily bring about a paradigm change. For the sake of analyzing the notions of progress and scientific revolution, it will be possible to confine the analysis to some of the major theoretical innovations – the transition from a static to an evolving universe, the notion of space-time and Einstein's equivalence principle, the role of thermodynamics - in so far as they can be accounted for in terms of the surgical interventions on the conceptual networks.⁸ These deletions, additions, modifications and replacements will provide the evidence against which the two rival explanations can be tested. As the story can be told in terms of differential surgery, which is carried out on the various components, it should be possible to compare and evaluate these two rival explanations in the light of the available evidence. Given the evidence, it should then be possible to infer the most plausible account of some of the major theoretical discoveries in the history of cosmology. It is the thesis of this paper that the 'chain-of-reasoning' model accounts better for the evidence than either Kuhn's paradigm or developmental models, simply because it offers a more balanced approach to the lines of reasoning that link the various cosmological models.

⁸ The brief history follows the exposition in Kragh (2007)

This thesis is borne out by a consideration of some of the major lines of descent in the recent history of astronomy and cosmology. Many of the discoveries in astronomy from Newton to Einstein fit neatly into the classical tradition. These were either of an *observational* kind – for instance, the Bradley’s observations of stellar aberration (1728), Wilhelm Herschel’s discovery of Uranus (1781) and Johann Galle’s detection of the planet Neptune (1846) after both J.J. Leverrier and J. C. Adams had predicted its existence from the application of Newtonian mechanics; Foucault’s pendulum experiment (1850); or they were of a *theoretical* kind – like Kant’s cosmological island view of the universe (1755), also derived from an application of Newton’s principles to cosmology and Laplace’s nebular hypothesis (1796). The classical paradigm had some notable puzzles to deal with – the nature of gravitation and Olbers’ paradox. But in Kuhnian terms these problems could be regarded as puzzles, which the paradigm could be expected to solve, rather than anomalies, which are persistent disagreements between the theory and empirical results. The first truly revolutionary challenge appeared with Einstein’s General theory of relativity (1916). In order to assess the transition from the old to the new cosmology let us consider three stages of its development.

1. The role of thermodynamics and statistical mechanics in cosmological thinking.
2. The notion of space-time.
3. The transition from a static to an evolving universe.

Ad 1) Thermodynamics and statistical mechanics emerged in the 1850s, during the heyday of classical physics, in an attempt to understand the efficiency of steam engines, without any reference to cosmology. Its central notions for present purposes are the Second law of thermodynamics and the statistical notion of entropy, expressed in Boltzmann’s equation $S = k \ln W$, where k is Boltzmann’s constant and W is the thermodynamic probability, which expresses the number of micro-states compatible with a given macro-state. Although entropy was originally defined for closed systems, in a state of equilibrium, it was applied to the universe in the popular notion of the ‘heat death’. W. Thomson (1852) spoke of ‘a universal tendency in nature to the dissipation of mechanical energy’ and concluded his survey with the ominous warning that ‘the Earth was and will again be unfit for human habitation.’

L. Boltzmann, like Thomson, lifted the notion of entropy to a cosmological level in an attempt to identify the arrow of time. Whilst it is generally accepted that entropy increases to a maximum in a closed system, like a container of gas molecules, Boltzmann assumes that the Second law can be applied, under certain reservations, to the whole universe.

People have been amazed to find as an ultimate consequence of this proposition that the whole world must be hurrying towards an end state in which all occurrences will cease, but this result is obvious if one regards the world as finite and subject to the second law. (Boltzmann 1905, p. 170)

These early speculations about the heat death – the gradual dissipation of energy such that all energy differentials will disappear, turning the universe into a lifeless wasteland, in which entropy is maximized – stand in stark contrast to the Newtonian view of a universe, which is infinite in both space and time. Modern cosmology assumes that at least ‘our’ universe – which may be part of a multiverse – started life in a Big Bang (13.7 billion years ago) and it is then left with the question of the eventual fate of the universe. Different scenarios have been envisaged but for present purposes it is significant that according to latest findings the universe accelerates and will not end in a Big Crunch – or a return to its initial condition. According to current cosmologies, our universe seems to be characterized by asymmetric boundary conditions, which determine its actual behaviour. The universe starts in a low-entropy Big Bang but is expected to collapse into high-entropy black holes, which will eventually evaporate to a state of even higher entropy, resembling a ‘heat death’. The relaxation time, τ , of thermodynamic systems is much shorter than the lifetime of the universe, T , which according to current calculations of the evaporation of black holes seems to amount to a lifetime of approximately 10^{100} years. Such an asymmetry suggests that the universe displays a cosmic arrow of time.

In terms of continuity it is to be noted that the application of the notion of ‘heat death’ to the universe occurred during the reign of the classic tradition in astronomy, which originated in Newton, but underwent a long period of gestation until it was accommodated in modern cosmology, now under the notion of Big Chill. As far as this central notion is concerned it is not a case of ‘local untranslatability’; nor is the new notion of space-time which applies retrospectively to older theories. It is a case of retrospective accommodation.

Ad 2) In his later work, Kuhn still speaks of ‘crises’, which occur when communication breaks down, due to the emergence of different lexicons. (Kuhn 1990/2000, p. 100) When Einstein developed the General theory of relativity, cosmology was not in a state of crisis. Rather the General theory was born out of a desire to overcome limitations in the Special theory of relativity. Hermann Minkowski developed the notion of space-time in order to provide a four-dimensional geometric model for the Special theory of relativity. Although the Special theory of relativity already departed from the Newtonian model in that it replaced Newton’s notions of absolute time and space by relativistic notions of temporal and spatial intervals, whose lengths depend on the velocity of the reference frame, from which they are measured – leading to the notions of relative simultaneity, time dilation and length contraction – it is still committed to a ‘privileged’ inertial reference frame, in which acceleration and gravity play no part. But Einstein’s equivalence principle between inertial and accelerated frames showed the need for a general principle of relativity, in which no reference frame enjoyed any privileged status. The consequence of this way of thinking led to a radical review of the notion of space-time. The remarkable feature of the General theory is that space-time ceases to be an inert background canvass. In the General theory the space-time structure itself becomes, in Wheeler’s famous words, fully dynamic in the sense ‘that matter tells space-time how to curve and curved space-time tells matter how to

move.’ Einstein’s General theory fundamentally changes our understanding of ‘gravity’, which was a puzzle for Newton, by replacing it with the notion of space-time curvature and non-Euclidean geometries. The General theory demonstrated its theoretical fruitfulness with the prediction of black holes. In its further development through Georges Lemaître and others it eventually gave rise to the Big Bang singularity, for which strong evidence emerged in the discovery of cosmic microwave background radiation (1965). Later the original Big Bang idea was refined by the introduction of the notion of inflation. The notion of space-time presents a remarkable shift away from the observation of the universe to the theoretical understanding of the whole universe in terms of space-time structure. (Kragh 2007, §3.1.4)

Again, in terms of continuity it should be noted that the notion of space-time can be formulated in the language of differential geometry, which is a coordinate-free formulation and not paradigm- or lexicon-dependent in the Kuhnian sense. That is, it is neutral with respect to different ‘paradigms’ or ‘lexicons’, such that it can be applied to different space-time theories – Newtonian mechanics, the Special and General theory of relativity - an application, which highlights the similarities and dissimilarities of space-time models in the classical and relativistic tradition. Given that the notion of space-time, in its coordinate-free formulation, can be applied to both Newtonian mechanics and relativistic mechanics means, in Kuhnian terms, that it does not change its meaning, and arguably not even its reference.

Ad 3) Einstein’s General theory of relativity implied the model of a static universe, which, like Newton’s, was infinite in time but finite in space. The inference of a Big Bang origin from the expansion of the universe, as expressed in Hubble’s law, was not the work of Edwin Hubble. Hubble’s discovery of the recession of the galaxies was made independently of the General theory. The discovery of a dynamic universe was the result of an application of the equations of the General theory to the universe by Alexander Friedman (1922, 1924) and Georges Lemaître (1927). Although the transition from a static to an evolving universe marks another significant shift in our understanding of the universe, it should be noted that an evolving universe is already part of the Kantian cosmology (1755). Kant explains the current state of the universe – its constellation of galaxies as a nested hierarchy – as a result of the application of Newtonian laws to some sort of original chaos. The modern universe looks quite different from Kant’s island universe, since Kant argued in terms of Newtonian mechanics, whilst modern cosmology applies the General theory of relativity and Quantum Mechanics to cosmological events. The application of quantum mechanics to cosmology leads to the recent development of quantum cosmology, which employs the notion of decoherence (or the dislocalization of quantum interference into the environment) to explain the emergence of classical space-time. Classical space-time now emerges from a fundamental quantum level through mechanisms of decoherence, i.e. the transition from a time-less Wheeler-de Witt equation to the Schrödinger equation. (Kiefer 1996) It is now generally assumed that the boundary conditions of the universe are asymmetric, thus bestowing a cosmological arrow of time. In such a model of an expanding and accelerating

universe, questions of the beginning and the eventual fate of the universe arise. The assumption of a Big Bang beginning of the universe is now being challenged and replaced by the idea of a multiverse. One concern about the Big Bang is that it is put in 'by hand' when the low-entropy initial conditions of the universe should be derived from more fundamental, dynamic processes, as they are envisaged in various cosmological scenarios, like oscillating and cyclic universes or even baby universes. (See Carroll 2010 for an overview)

Thus there exist a number of continuities and discontinuities between older and newer cosmological models and the question arises whether these lines of descent are better accommodated in the 'chain-of-reasoning' model, the Kuhnian paradigm model or the newer developmental model?

V. New view: Chain-of-reasoning model

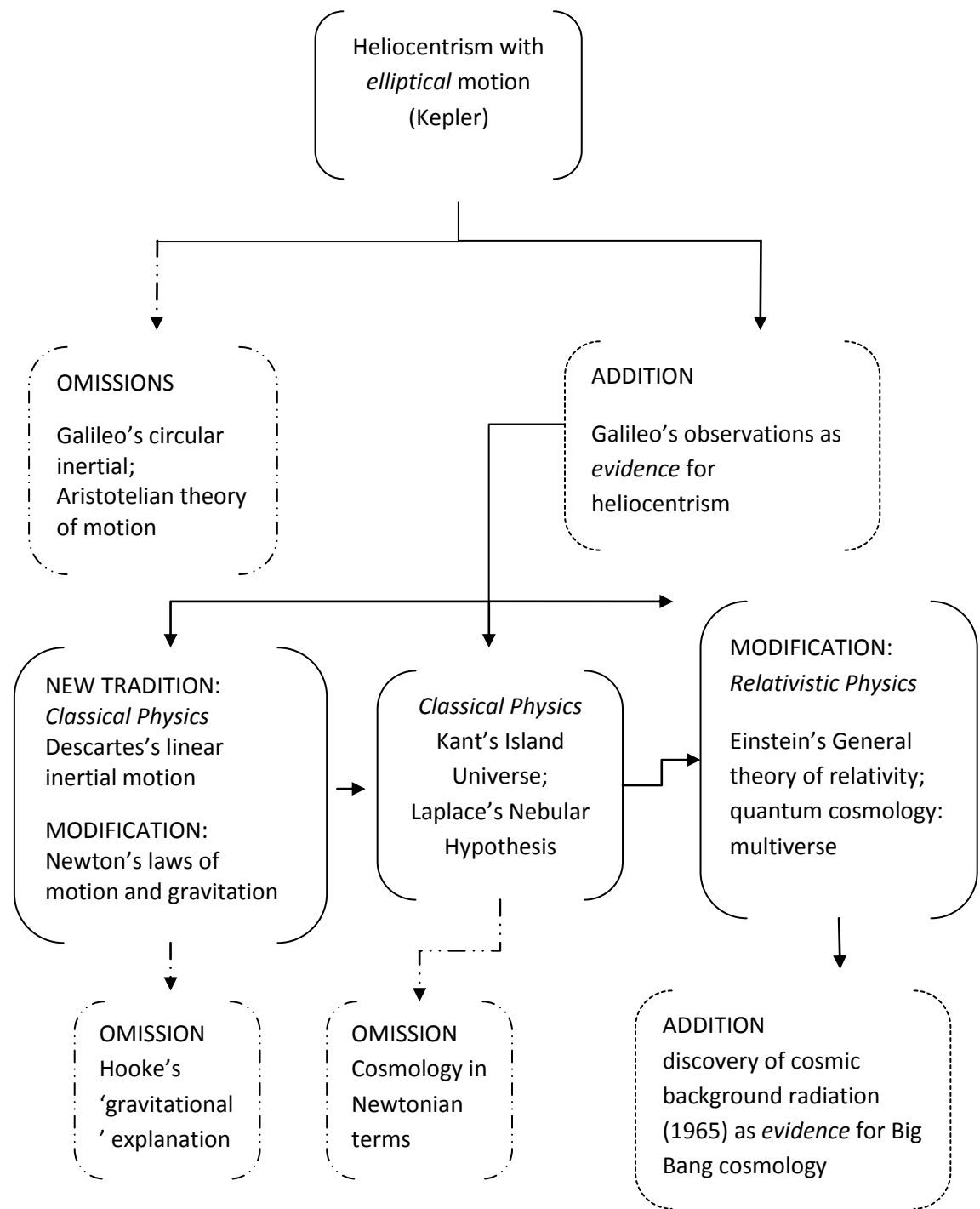
None of the developments in astronomy and cosmology reviewed here were triggered by a crisis or striking anomalies in previous traditions. Furthermore, some of the central notions, like the Big Bang singularity, the arrow of time, the Heat Death, the evolving universe and space-time, are shared by the traditions. The General theory of relativity was such a profound theoretical change that, on Kuhn's view, its emergence would have required a crisis. (Kuhn 1961, §4) Even in the absence of a crisis there needs to be some event, which makes scientist question the 'rigidity of normal science' but it is difficult to pinpoint such Kuhnian events in the recent history of astronomy and cosmology. (See Kuhn 1970a, p. 181) Nor is it the case that the history of astronomy/cosmology was predominantly concerned with puzzle solving (mopping-up operations). It is true that Kuhn rejects the view that normal science 'is a single monolithic and unified enterprise'. (Kuhn 1970a, p. 49; cf. Kuhn 1991/2000, p. 119) But Kuhn does have a tendency to characterize first normal science and later lexicon-using scientific communities as being marked by a paucity of competing theories or lexicons. However, as several commentators have pointed out (Earman 1993; McMullin 1993) even periods of 'normal' science are characterized by a competition between competitors. To mention two examples: even when it looked as if the Copernican model was gaining predominance in the 17th century, G. Riccioli's textbook of astronomy (1651) still lists 5 competing models; the same is true of the General theory of relativity – it was never without competitors; and today's cosmology is no exception as evidenced in the competition between string theory and loop quantum gravity. This means that although there is a predominant theory, there is no convergence to a single theory.

According to Kuhn's later views, revolutionary changes – speciation – are still accompanied by non-cumulative growth. (Kuhn 1987/2000, p. 14; 1991/2000, pp. 119-20) But note that lexical divergence may neither be a sufficient nor a necessary condition for revolutionary change. As Kuhn emphasizes repeatedly, the term 'planet' underwent significant meaning

change in the transition from geocentrism to heliocentrism, yet by his own early assessment and that of other historians, Copernican heliocentrism does not amount to a scientific revolution. J. B. Lamarck introduced a major taxonomic change when he departed from tradition and made species variable and subject to evolution, when the earlier tradition had regarded species as 'fixed'. Yet Lamarck's theory of progressive evolution is not regarded as a scientific revolution, mainly because it lacks a believable mechanism to explain evolutionary changes in species. On the other hand, notions like 'space-time', 'heat death' or 'evolving universe' can be cast in Newtonian and relativistic language, and yet, at least the General theory of relativity is truly a revolutionary theory. Kuhn also uses the notion of 'mass' as an example of a term, which becomes incommensurable between Newtonian and relativistic physics. Yet relativistic mass approximates to Newtonian mass when relativistic speeds are replaced by classical speeds. It seems that for a scientific revolution more is needed than a consideration of the career of central terms. What matters are the reasons why these lexical notions undergo linguistic changes. (Cf. Shapere 1989, §4) Such reasons often take the form of new explanatory principles (for example Darwin's mechanism of natural selection or Einstein's field concept of the space-time continuum), which explain the observable phenomena.

What emerges from the brief survey of cosmology since Copernicus is that there are clear lines continuity and discontinuity; and further that even the older traditions contain embryonic anticipations of much later developments. Although Kuhn's paradigm model allows for lines of descent, his emphasis on discontinuities prevents his paradigm model from adequately explaining the history of astronomy from Copernicus to Einstein and beyond. His newer developmental model focuses on the description of lexical changes (and speciation), which may however be neither necessary nor sufficient for revolutionary change. It is therefore appropriate to turn to the 'chain-of-reasoning' model, with its emphasis on lines of continuity and discontinuity, where these lines of descent are governed by reasons. (Figure III) Reasons can be provided in several ways: a) intersubjective empirical data as a result of objective observation or experiments; b) mathematical considerations, as in the derivation of an empirical law from more fundamental laws; c) logical considerations, as in Galileo's famous tower thought experiment, with which he attempted to disprove the Aristotelian theory of motion; or d) plausibility considerations, as illustrated in Maestlin's arguments against geocentrism.

Figure III: 'Chain of Reasoning model', showing surgical interventions (additions, modifications, omissions) and lines of descent



As remarked above, Kuhn stresses that the evaluation of theory change is governed by values, such as accuracy, fruitfulness and the ability to solve outstanding problems *quantitatively*. But quantitative problem-solving involves evidence- both empirical and theoretical. A consideration of some plausibility arguments in the history of astronomy shows that reasons do not just function as values, which can be interpreted in different ways, and whose application may change over time; the reasons function as rules and carry epistemic import. Consider the dispute between proponents of geocentrism and heliocentrism at the beginning of the 17th century, which centred on epistemic reasons, in the guise of plausibility arguments.

One plausibility argument, used by Maestlin and Kepler against geocentrism, concerns the apparent rotational velocity of the outer sphere of ‘fixed’ stars. On both the geocentric and the heliocentric model the rotation of the sphere of ‘fixed’ stars requires explanation but the physical consequences of the explanation are strikingly different, depending on whether a stationary or rotating Earth is assumed.

Consider the divergent probabilities, which follow from a modern reconsideration of the angular velocities involved under the two scenarios.⁹ Under some simplifying assumptions, the angular velocity of the Earth for an observer at the equator is $464 \frac{m}{s} = 1670 \frac{km}{h}$. The geocentric view, by contrast, has to assume an angular velocity of the ‘fixed’ stars about the stationary Earth. A calculation produces a value of $4.62 \times 10^5 \frac{m}{s} = 1.66 \times 10^6 \frac{km}{h}$. (Weinert 2010) It is such an enormous rotational velocity of the stars – 1.66 million kilometres per hour, compared to 1670 km per hour for the Earth at the equator – which the Copernicans considered improbable on mechanical grounds. By comparison, the orbital velocity of the Earth around the sun is 30km/s and the velocity of the solar system around the galactic centre is 225km/s. Thus Copernicans, like Kepler and Maestlin, base their plausibility arguments on a physical feature of the heliocentric model. The daily rotation of the Earth is the physical cause of the apparent rotation of the ‘fixed’ stars. This rotation is more probable, given the speeds involved, than the rotation attributed to the fixed stars around a stationary Earth in the geocentric model. Such probability considerations are clearly not lexicon-specific (cf. Kuhn 1990/2000, pp. 99-100; 1991/2000, p. 113) but coordinate-free, like the language of differential geometry.

⁹To arrive at these figures we assume a circular motion of the earth on its own axis at the equator and a circular motion of the sphere of the fixed stars in a 24 hour period around the earth. The equation for the angular

velocity in both cases is $v_{Earth/Stars} = \omega r = d\pi f; f = \frac{1}{T} = 8.64^{-4} s$. The radius of the earth is

$6.37 \times 10^5 m$ and the radius of the earth-star distance is taken to be $1.27 \times 10^{10} m$ in line with Ptolemy’s views. Note that the angular velocity of the earth 45° to the north of the equator is only 1180km/h. If we adopt Maestlin’s smaller earth-star distance estimate - $1.5 \times 10^9 m$ - we get a rotational velocity of 1132 German miles per ‘pulse’. If we count 4000 pulses per hour and take the traditional measure of 1 German mile = 7532 m, the figure increases to $3.4 \times 10^7 km/hr$, which, in Maestlin’s words, ‘truly exceeds all belief.’ (Quoted from Tredwell, 2004, p. 318)

Similar plausibility arguments led to the downfall of the steady-state theory, as opposed to the Big Bang cosmology after the discovery of the cosmic background radiation (1965). It is said to be the afterglow of the Big Bang, and hence was interpreted as direct evidence for evolving universe scenarios. But the steady-state cosmology defended a ‘perfect cosmological principle’, according to which the universe is both ‘spatially and temporally homogeneous, which implied an eternal universe.’ (Kragh 2007, pp. 203-4) Hence the Big Bang theory makes the evidence, i.e. the background radiation at a temperature of 2.7K, more plausible than the steady-state cosmology. (See Appendix for an illustrative application of Bayesianism to cosmological theories.)

VI. Conclusion.

It was noted that there is some overlap between the ‘chain-of-reason’ model and Kuhn’s later ‘historical view’ but there are also some significant points of divergence.

- Kuhn continues to hold that a commitment to truth in the sense of Popper’s verisimilitude is ill-conceived, and opts instead for a redundancy theory of truth:

A new body of belief could be *more* accurate, *more* consistent, broader in its range of applicability, and also simpler without for these reasons being any truer. (Kuhn 1991/2000, p. 115; italics in original; cf. 1990/2000, p. 99)

- A whiff of relativism remains in Kuhn’s later work since the post-Darwinian Kantianism he adopts calls for an interdependence of lexicons and ontologies:

It is groups and group practices that constitute worlds (and are constituted by them). (Kuhn 1990/2000, p. 103; cf. 1986/2000, pp. 61, 85)

- Incommensurability – as the local untranslatability of some central terms between different lexicons - is still central to an evaluation of the scientific enterprise. (Kuhn 1986; 1987; 1991)
- Kuhn distinguishes between a diachronic and a synchronic sense of scientific development. (1990/2000, p. 97; cf. Díez 2007). The synchronic sense, as the increasing specialization of scientific disciplines, emphasises social aspects of scientific research. When scientific traditions split, it should come as no surprise that scientific sub-disciplines develop new lexicons. (See Wray 2011, Ch. 7) It is the diachronic sense, as the relation between successive ‘paradigms’, ‘theories’ or ‘lexicons’, which require an adequate theory of scientific revolutions.

The ‘chain-of-reason’ model will agree, in part, with Kuhn’s developmental approach regarding matters of evaluation. Evaluation is a question of the rationality of incremental belief changes rather than of the rationality of belief *tout court*. (Kuhn 1991/2000, pp. 112-4) Such an evaluation was applied to the brief history of cosmology but it made no reference to the lexicon-dependence of world views, to the importance of incommensurability, and to

breakdowns in communication. It assumed that it was legitimate to consider reasons for surgical interventions, which lead to theory transitions, without relativization to lexicon-stipulatable worlds. The outstanding question remains whether a 'chain-of reason' approach needs to take into consideration the implications of Kuhn's post-Darwinian Kantianism.

Integrating these insights takes us to an analytic four-stage model of a scientific revolution as a series of successive events:

1. a turn or switch of perspectives, which often involves a questioning of existing presuppositions, like circular motion of planets or a static universe, and the perception of a problem, like the failure of the ancients to consider a coherent planetary system, which is not necessarily an anomaly;
2. the introduction of new methods, principles of explanation and techniques with problem-solving ability, like calculus, differential geometry or unification; it is these underlying principles, which are the drivers of change, as can be seen in the emergence of Newtonian heliocentrism, Darwinian evolution, Einstein's General theory of relativity or the unification of previously separated domains (e.g. electricity and magnetism; quantum theory and general relativity).
3. the emergence of a new tradition through differential 'chain-of-reasoning' transitions, as a result of the problem-solving success of the emergent tradition;
4. convergence of expert opinion on to a new tradition; this convergence does not exclude the coexistence of alternative models within the new tradition.

This model of scientific revolutions reflects Kuhn's view that scientific revolutions are not point-like, unique events but unfold over a period of time. (Kuhn 1962) It is a transition from convergent to divergent thinking. (Kuhn 1959) But this transition neither takes the form of a psychological gestalt switch, which the later Kuhn abandoned (since his emphasis was on research communities); nor does it create 'lexically-stipulatable worlds'. It is justified by theoretical and empirical reasons, which according to the 'chain-of-reasoning' approach and Bayesian considerations have more epistemic weight than the loftier values, on which Kuhn focuses. (Cf. Shapere 1989; Cohen 1985; Friedman 2001) The divergent assessment of the status of the Copernican model, mentioned above, and the consideration of the brief history of cosmology, may well reflect not only the extent to which lines of descent are to be considered but also which lines of descent are to be excluded or included in the surgical operations. Ultimately, the difference between Kuhn's developmental account and the 'chain-of-reasoning' model may well reside in this difference.

Appendix

An objective Bayesian approach can illustrate how such criteria as accuracy and scope of evidence can be decisive in theory choice in a way that would be acceptable to the later Kuhn.

The introduction of terms like ‘plausibility’ and ‘probability’ naturally invites a consideration of theory choice in terms of Bayesianism.¹⁰ In order to avoid the problem of the determination of the probability of the priors, $P(h|E)$ and the expectedness, $P(E|B)$ ¹¹ it will be convenient to restrict the discussion to a comparison of likelihoods or a likelihood ratio: that is how likely the rival hypotheses make the available evidence. (Salmon 1990; Weinert 2009)

Following Salmon (1990, p. 192), the likelihood ratio can be expressed in the equation

$$\frac{P(T_1|E \& B)}{P(T_2|E \& B)} = \frac{P(E|T_1 \& B)}{P(E|T_2 \& B)} \times \frac{P(T_1|B)}{P(T_2|B)} \quad (1)$$

from which it follows that

$$P(T_2|E \& B) > P(T_1|E \& B)$$

iff

$$\frac{P(E|T_2 \& B)}{P(E|T_1 \& B)} > \frac{P(T_1|B)}{P(T_2|B)} \quad (2)$$

Hence, T_2 should be preferred over T_1 , after new evidence has come to light, if equation (2) is satisfied. If we let T_1 stand for either geocentrism or the steady-state cosmology respectively, and T_2 for the Copernican model or the Big Bang model respectively, it can easily be seen that this condition is satisfied. For the probability values for the likelihoods only need to diverge by 0.1 units, say $P(E|T_2 \& B) = 0.4$ and $P(E|T_1 \& B) = 0.3$ for the inequality to be satisfied, if we assume, plausibly, that $P(T_1|B) = P(T_2|B) = y$, where ‘y’ is some values

¹⁰ Although Salmon restricts the consideration of plausibility arguments, as contained in Bayesian considerations, to the choice of prior probabilities, this restriction is not of much use in periods of revolutionary fervour, since often very unlikely hypothesis – unlikely as measured against the background knowledge – emerge. Therefore plausibility arguments must be used for the comparison of likelihoods (Weinert 2009). This brief exercise in the application of the Bayesian apparatus is not meant to revive the old debate about the compatibility of Bayesianism with Kuhn’s views on theory change (see Worrall 2000) but merely serves illustrative purposes. See Williamson (2010) for an introduction to objective Bayesianism.

¹¹ The relationship between the expectedness and the prior probabilities and the likelihoods is:
 $P(E|B) = P(T|B)P(E|T \& B) + P(-T|B)P(E|-T \& B)$

smaller than or equal to 1.¹² The latter assumption is justified in the case of the before-mentioned astronomical models, because the prior probabilities of heliocentrism and geocentrism respectively, were regarded to be approximately equal, as mentioned by Osiander.

These likelihood considerations do not constitute knock-down arguments, because the discredited theories can introduce *ad hoc* hypotheses or modifications. But the question is always at what price such modifications are introduced; the fact is that evidence in favour of one theory and against another is usually cumulative. As W. Salmon observed, ‘the algorithms are trivial; what is important is the scientific judgement involved in assessing the probabilities that are fed into the equations.’ (Salmon 1990, p. 201)

If plausibility considerations are used for the comparison of likelihoods, Bayesianism allows us to speak of the probability of competing ‘theories – thus leaving aside the further question whether the progress of science is to be judged in Lamarckian or Darwinian terms. The ‘chain-of-reasoning’ model generalizes such considerations and states that reasons – both empirical, like new discoveries, and theoretical, like plausibility arguments – lead to transitions to new traditions.

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¹²A similar point can be made with respect to the phases of Venus. If the phases of Venus – full, $\frac{3}{4}$, $\frac{1}{2}$, crescent – are regarded as evidence for or against the heliocentric and geocentric system, then this evidence bestows credibility on the Copernican system whilst the Ptolemaic system renders the evidence not just improbable but impossible. On the Ptolemaic model we would at best see a crescent.

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